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Human Factors Issues When Operating Unmanned Underwater Vehicles

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Defence R&D Canada
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Abstract

There has been a great deal of human factors research on unmanned air vehicles (UAVs) and unmanned ground vehicles (UGVs) in large part due to a high number of operator related mishaps. However, there is very little research examining the unique human factors problems associated with unmanned underwater vehicles (UUVs). The lack of research is surprising as there are frequent anecdotal accounts of remotely operated vehicle (ROV) entanglement, collisions, and failures. In addition, militaries are now using UUVs for search and rescue and mine countermeasure (MCM) operations and in the future, UUVs will take on critical roles in intelligence, surveillance, and reconnaissance (ISR), anti-submarine warfare (ASW) and even time critical strike operations. In this paper, it is argued that the underwater environment presents unique challenges to operating UUVs that are different from the challenges of UGV and UAV systems. Several common human factors problems are discussed when using UUVs, including the loss of sensory cues and spatial awareness, the control of the remote vehicle, problems with situation awareness (SA) and workload, problems with trust in automation, and challenges with human robot communication. In each case, these issues are discussed with respect to underwater operations.

Résumé

En bonne partie en raison du nombre élevé de contretemps liés aux opérateurs, on a fait beaucoup de recherches sur les facteurs humains liés aux engins télépilotés aériens (UAV) et aux engins télépilotés terrestres (UGV). Il existe cependant très peu de recherches sur les problèmes particuliers aux facteurs humains associés aux engins télépilotés sous-marins (UUV). Ce faible nombre de recherches est surprenant, car il y a souvent des comptes rendus anecdotiques d'enchevêtrements, de collisions et de pannes de ROV. De plus, des militaires utilisent maintenant les UUV pour des opérations de recherche et sauvetage ainsi que de lutte contre les mines (LCM) et, dans le futur, les UUV joueront des rôles essentiels dans le renseignement, la surveillance et la reconnaissance (RSR), la lutte anti-sous-marine (LASM) et même dans les opérations offensives à durée critique. Dans le présent document, on allègue que le milieu sous-marin présente des défis particuliers à l'exploitation d'UUV qui diffèrent de ceux que présentent les systèmes UGV et UAV. Plusieurs problèmes courants liés aux facteurs humains sont traités lors de l'utilisation d'UUV, notamment la perte de repères sensoriels et d'orientation spatiale, la commande de l'engin télépiloté, les problèmes de conscience de la situation et de la charge de travail, les problèmes de confiance en l'automatisation ainsi que les défis que constitue la communication entre les humains et les robots. Dans chaque cas, on traite de ces questions en rapport avec les opérations sous-marines.

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Executive summary

Human Factors Issues When Operating Unmanned Underwater Vehicles:

Geoffrey Ho; Nada J. Pavlovic; Robert Arrabito; Rifaat Abdalla; DRDC Toronto TR 2011-100; Defence R&D Canada – Toronto; March 2011.

Introduction or background: Unmanned underwater vehicles (UUVs) are robotic vehicles that can operate underwater. They are controlled either remotely by a human operator [i.e., remotely operated vehicles (ROVs) or autonomously through software (i.e., autonomous underwater vehicles (AUVs)]. Both these types of UUVs can be equipped with various payloads such as sonar, sensors, cameras and manipulators which allows them to perform a wide range of tasks. Over the past decade, militaries have been increasingly using unmanned underwater vehicles (UUVs) for conducting military operations such as intelligence, surveillance, and reconnaissance (ISR), oceanography data collection, and most notably, mine countermeasures (MCM).

Despite the dramatic increased use of UUVs, there is little research examining the human factors issues associated with operating and monitoring UUVs. Furthermore, there is no research examining potential human factors issues for the predicted capabilities of future UUVs (e.g., greater autonomy) and their predicted future operations (e.g., swarms of UUVs for underwater communications networks). In this report, a summary of current human factors issues and potential human factors problems arising in future maritime operations utilizing UUVs is provided and discussed.

Results: Human factors issues are identified for operating both ROVs and AUVs. For ROVs, the human factors problems primarily deal with having to remotely operate the vehicle. The operator has limited spatial awareness because of impoverished visual cues. The underwater environment is dark and often turbid, the vehicle's video camera has a limited field of view (FOV), and depth perception is impaired. The ROV operator also has the difficult task of controlling and navigating the vehicle. ROVs move under 6 degrees of movement freedom and their position must continually be corrected for ocean currents and changes in water density. The operator must also manage the ROV's umbilical cable which provides the vehicle with communications and power. Umbilical cable entanglement and drag can greatly affect the ROV's performance.

In contrast, AUVs have no umbilical cable and are pre-programmed to swim to specific waypoints to collect data and then return to home base. They do not require an operator to control the vehicle so problems related to vehicle control are eliminated. However, due to difficulties transmitting information wirelessly underwater, there is commonly no situation awareness (SA) of the AUV's position or health status. If there is some basic telemetry, the information is commonly delayed by tens of seconds and is subject to inaccuracies. Hence, there is no guarantee that an AUV has performed its task as programmed. As a result, an operator's trust that an AUV will successfully complete its mission is commonly low.

Despite the human factors problems, there is a trend towards having AUVs operate in swarms with greater autonomy. These AUVs would be responsible for more complex tasks that would require the vehicles to collaborate during missions. The low trust, the lack of operator SA and the

possibility of AUV failures is a great concern for the successful completion of these future operations.

Significance: The Canadian Forces (CF) has ongoing plans to incorporate more unmanned systems including UUVs to their maritime defence strategy [Department of National Defence (DND) Canada, 2001]. The findings outlined in this report have strong implications for operating UUV systems. This report summarizes the human factors issues associated with operating UUVs and will provide the CF with important considerations for the procurement of future UUVs, the training of personnel, and developing the procedures necessary to operate the vehicles and complete missions effectively.

Future plans: The human factors problems identified in this report are based on knowledge obtained from existing literature on unmanned vehicles, oceanography, diving, and human factors. However, there is little empirical data that have tested the magnitude of problems. A research program needs to be established to study these problems in more detail and in a systematic fashion. As well, countermeasures to these problems need to be explored to provide the CF with options on overcoming the difficulties of operating UUV systems.

Sommaire

Questions relatives aux facteurs humains lors de l’exploitation d’engins télépilotés sous-marins

Geoffrey Ho; Nada J. Pavlovic; Robert Arrabito; Rifaat Abdalla ; DRDC Toronto TR 2011-100 ; R & D pour la défense Canada – Toronto; mars 2011.

Introduction ou contexte : Les engins télépilotés sous-marins (UUV) sont des véhicules robotisés pouvant fonctionner sous l’eau. Ils sont commandés à distance par un opérateur humain [p. ex. engins télépilotés (ROV) ou autonomes au moyen d’un logiciel (p. ex. engins sous-marins autonomes (AUV)]. Ces deux types d’UUV peuvent être équipés de différentes charges utiles, comme un sonar, des capteurs, des caméras et des manipulateurs, ce qui leur permet d’exécuter une vaste gamme de tâches. Au cours de la dernière décennie, les militaires ont utilisé de plus en plus les engins télépilotés sous-marins (UUV) pour effectuer des opérations militaires comme le renseignement, la surveillance et la reconnaissance (RSR), la collecte de données océanographiques et, plus particulièrement, la lutte contre les mines (LCM).

Malgré l’augmentation spectaculaire de l’utilisation des UUV, presque aucune recherche n’étudie les questions relatives aux facteurs humains associées à l’exploitation et à la surveillance des UUV. De plus, aucune recherche n’étudie les questions potentielles relatives aux facteurs humains concernant les capacités prévues des futurs UUV (p. ex. une autonomie supérieure) et leurs opérations futures prévues (p. ex. essaims d’UUV pour réseaux sous-marins de télécommunications). Dans le présent compte rendu, un sommaire des questions actuelles relatives aux facteurs humains et aux problèmes potentiels relatifs aux facteurs humains susceptibles de survenir dans le cadre de futures opérations maritimes utilisant des UUV est fourni et traité.

Résultats : Des questions relatives aux facteurs humains sont identifiées en rapport avec le fonctionnement des ROV et des AUV. Dans le cas des ROV, les problèmes relatifs aux facteurs humains concernent principalement le fait d’avoir à les faire fonctionner à distance. L’opérateur dispose d’une orientation spatiale limitée en raison de l’appauvrissement des repères visuels. Le milieu sous-marin est sombre et souvent trouble, le champ de vision de la caméra vidéo de l’engin est limité et la perception du relief est moins bonne. L’opérateur d’un ROV se voit aussi confier la tâche difficile de la commande et de la navigation de l’engin. La liberté de mouvement des ROV est de 6 degrés, et on doit constamment en corriger la position en fonction des courants de l’océan et des modifications de la densité de l’eau. L’opérateur doit également gérer la liaison ombilicale du ROV, laquelle fournit à l’engin les télécommunications et l’alimentation. L’enchevêtrement et la traînée de la liaison ombilicale peuvent grandement altérer les performances du ROV.

En revanche, les AUV ne possèdent pas de liaison ombilicale et ils sont préprogrammés pour naviguer jusqu’à des points de cheminement spécifiques, afin de recueillir des données puis de retourner à leur base d’attache. Comme les AUV n’ont pas besoin d’opérateur pour les commander, les problèmes liés à la commande de l’engin sont éliminés. Cependant, en raison des difficultés éprouvées en matière de transmission sous-marine sans fil de renseignements, il n’y a généralement aucune connaissance de la situation (CS) relativement à la position ou à l’état de

l'AUV. S'il y a des dispositifs de télémesure de base, les renseignements sont généralement retardés de dizaines de secondes et ils peuvent comporter des inexactitudes. Il n'existe donc aucune garantie qu'un AUV a exécuté sa tâche comme il avait été programmé pour le faire. Par conséquent, la confiance d'un opérateur à l'effet qu'un AUV s'acquittera avec succès des missions qui lui ont été confiées est généralement faible.

Malgré les problèmes relatifs aux facteurs humains, la tendance est de faire fonctionner les AUV en essaims avec une plus grande autonomie. Ces AUV seraient responsables de tâches plus complexes qui nécessiteraient la collaboration des engins pendant les missions. La faible confiance, le manque de CS de l'opérateur et la possibilité de pannes des AUV constituent une grande préoccupation quant à la réussite de ces futures opérations.

Importance : Les Forces canadiennes (FC) possèdent des plans continus pour intégrer davantage de systèmes télépilotés, notamment des UUV, dans leur stratégie de défense maritime [ministère de la Défense nationale (MDN) du Canada, 2001]. Les conclusions présentées dans le présent compte rendu comportent d'importantes implications relativement aux systèmes UUV. Le présent compte rendu résume les questions relatives aux facteurs humains associées à l'exploitation des UUV, et il fournira aux FC des facteurs importants à considérer quant à l'acquisition de futurs UUV, à la formation du personnel et à l'élaboration des procédures nécessaires à l'exploitation des engins et à la réussite des missions.

Perspectives : Les problèmes relatifs aux facteurs humains que renferme ce compte rendu sont basés sur des connaissances obtenues dans la littérature existante sur les engins télépilotés, sur l'océanographie, sur la plongée et sur les facteurs humains. Il y a cependant peu de données empiriques ayant contribué à tester l'ampleur des problèmes. Il faut établir un programme de recherche pour étudier entièrement et plus en détail ces problèmes de façon systématique. De plus, on doit explorer les mesures correctives visant à pallier ces problèmes pour fournir aux FC des solutions visant à surmonter les difficultés inhérentes au fonctionnement des systèmes UUV.

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1 Introduction

1.1 Background

The use of unmanned systems in militaries around the world has increased notably over the past three decades. Unmanned systems have been vital for conducting intelligence, surveillance, and reconnaissance (ISR), for providing ordnance detection and disposal, and for conducting critical strike operations (United States Department of Defense (USDOD), 2007). However, the use of unmanned systems in maritime operations is still relatively new even though unmanned systems are well suited for underwater tasks. The underwater environment poses particular challenges to humans. Human life cannot be sustained underwater without life support and personal protective equipment and even with equipment, humans cannot remain underwater for extended periods of time. Thus, the use of unmanned underwater vehicles (UUVs) is an ideal alternative for performing many maritime military operations (US Navy, 2004; Department of National Defence (DND) Canada, 2001). The Canadian Forces (CF) has ongoing plans to incorporate unmanned systems in many future military operations, including underwater intervention [DND Canada, 2001; Withington, 2010].

UUVs are robotic vehicles that operate underwater. They are controlled either remotely by a human operator or autonomously through software. UUVs can be equipped with various payloads such as sonar, sensors, cameras and manipulators which allows them to perform a wide range of functions. Today, UUVs are used to survey the water and seabed, to look for underwater objects, to support divers during underwater construction and infrastructure maintenance, and increasingly, to support mine countermeasures (MCM) operations. The data gathered by UUVs can be post-processed upon retrieval and, in some rare cases, the data can even be monitored in real-time (or near real-time) by a human operator (Beaton, 2007).

Similar to their air and ground counterparts, UUVs have a great potential for performing many of the "dull, dirty and dangerous" underwater missions (USDOD, 2007). However, with the introduction of unmanned systems in the underwater environment, a host of human factors problems is starting to emerge. A key contributor to these problems is the underwater environment itself. The characteristics of the underwater environment, such as high clutter density of the seabed and water turbidity can reduce visibility and affect the quality of sensor data. Adverse conditions in sea state such as changes in water density and strong currents can disrupt UUV navigation and manoeuvrability. In addition, communications technologies with the surface crew are highly restricted with respect to speed and bandwidth.

Yet, unlike unmanned aerial vehicles (UAVs) and unmanned ground vehicles (UGVs), there is little research examining current human factors issues associated with operating and monitoring UUVs. Most of the current research that does exist pertaining to operator related issues with underwater vehicles primarily stems from disciplines such as engineering, computer science, and artificial intelligence rather than human factors. These articles laudably recognize the importance of the human-in-the-loop, but the primary focus of these articles is still the technology and not the operator. For example, several papers discuss the implementation of novel user interface concepts which are designed to support the operator (Garcia, Fernandez, Sanz, & Marin, 2010; Garcia, Prats, Sanz, Marin & Belmonte, 2010; Johnson, Patron, & Lane, 2007; Kleindiesnt & Lueth,

2009) but they fail to test the concepts on human participants; in fact, only one of these paper (Johnson et al., 2007) discuss any human factors methods applied in their interface design. Others have investigated technologies to aid the operator vision (Jeon, Lee, & Lee, 2001; Negahdaripour & Firoozfam, 2006) but again, these studies only focus on the development of the technology, not the performance of the users. The exception to this argument is the work by Donovan and her colleagues (Donovan & Triggs, 2006; Donovan, Triggs, Wharington, Henley, & Gaylor, 2004). Donovan and Triggs (2006) investigated operator spatial awareness when using two different types of interface concepts to show the remotely operated vehicle's (ROV's) attitude. Furthermore, Donovan et al. (2004) discuss the importance of situation awareness (SA) when operating underwater vehicles. With the exception of these two articles, our literature search was unable to find any other article directly related to the human factors of operating UUVs. In addition, there is no research examining potential human factors issues for the predicted capabilities of future UUVs (e.g., greater autonomy) and their predicted future operations (e.g., swarms of UUVs for underwater communications networks). In order to fill this gap in the literature, this report will provide a summary of current human factors issues and potential human factors problems arising in future maritime operations utilizing UUVs.

1.2 Purpose and Scope

The dramatic rise in the use of unmanned systems in military organizations around the world has led to a great deal of human factors research to understand human performance when monitoring and controlling the vehicles and to mitigate the high number of mishaps that have occurred with some UAV systems (Williams, 2004). However, this abundance of human factors research on unmanned systems has not extended to the investigation of human-related problems for operating UUVs. This is surprising because like UAVs, there is strong anecdotal evidence for frequent UUV mishaps. For example, ROVs can be difficult to control, and in cluttered environments, there are frequent reports that the umbilical cable can easily become tangled in debris or even tangled in the propeller of its surface vessel (Christ & Wernli, 2007). There are methods to reduce umbilical cable entanglement, but by and large, entanglement prevention is the result of the superior skills of the human ROV operator (Zand, 2005).

In addition to umbilical cable entanglement, there are a number of other documented human-related problems when operating UUVs including problems with perception, underwater navigation and orientation, interface design, and SA (Christ & Wernli, 2007; Donovan & Triggs, 2006; Donavan et al., 2004). Despite the fact that the CF will be employing UUVs in future maritime operations (CF, 2011), none of these human-related problems have been studied in-depth and little research has been dedicated to exploring countermeasures to these problems.

In this report, a number of human factors problems related to operating UUVs are discussed. While some of these problems are also evident in UAVs and UGVs (see Chen, Haas, & Barnes, 2007; Cooke, Pringle, Pedersen, Connor & Salas, 2006), this report supports the position that the human factors problems experienced when operating UUVs are unique to UUVs because of the nature of the underwater environment. The underwater environment produces additional constraints that are not experienced by unmanned aerial or ground vehicles. Thus, in Section **2**, this paper begins with an introduction to the underwater environment and a discussion regarding how the underwater properties impose unique human factors problems for operating remotely controlled vehicles. In Section **3**, a brief introduction to UUVs is provided. Specifically, two

broad classes of UUVs are described, ROVs and autonomous underwater vehicles (AUVs). The key characteristics of ROVs and AUVs and some of the typical tasks performed by these vehicles are discussed. Through an understanding of the underwater environment and the technological limitations of UUVs, Section **2** and Section **3** will set the context for Section **4**, which discusses several of the human factors problems associated with UUVs. These problems include underwater perception issues, problems with UUV controls and displays, SA and workload of human operators, low or poorly calibrated trust in UUV systems, and difficulties with human **-** robot communication underwater. The final section, Section **5** concludes this document with a discussion on future research needs.

2 The Underwater Environment

The ocean makes up approximately 71% of the earth's surface and remains largely unexplored and unknown (Kershaw & Cundy, 2000). Yet, the oceans are critical to our climatic and atmospheric conditions as they store much of the world's natural energy and food supply. Economically, the oceans act as a roadway for trading goods around the world. This dependence on our oceans and waterways makes them key areas of exploitation from adversarial groups. Even a threat of a mine in a port or shipping lane can cause major disruption to commercial shipping and Canada's economy (CF, 2011). Thus, protecting and securing the water is critical to Canada's security. To protect Canadian waters effectively, a thorough understanding of the underwater environment and how its properties affect underwater operations is essential.

Ocean temperatures vary seasonally from region to region. Solar radiation heats the water disproportionately depending on the sun's angle. As a result, surface water in low latitude areas near the equator is up to four times greater in temperature than surface water near the poles. In general, surface water temperature ranges from - 2ºC near the poles to about 30ºC near the equator (Kershaw & Cundy, 2000). Beneath the surface, water temperatures vary by depth and by latitude. At very high latitudes, the water temperature remains near zero throughout the water column. At mid to low latitudes, the upper zone of the water column (50m – 200m) remains close to surface water temperatures. From 200m to 1000m though, the water temperature falls sharply with declining depth. This zone is known as the thermocline zone. Beyond the thermocline zone, in the deep depths of the ocean, temperatures again are relatively stable and do not cool much more (Kershaw & Cundy, 2000).

The temperature of ocean waters, along with its salinity and pressure, contributes to the water's density. In general, warm water is less dense than cold water and low salinity water is less dense than high salinity water. Because temperature affects the density of water more so than salinity, the distinct layers of temperature also stratify the water column into distinct layers of water density. This difference in density along the water column is responsible for deep water circulation (Garrison, 2007; Kershaw & Cundy, 2000).

In contrast, the movement of the ocean surface is wind-driven. The wind blowing over the surface of the water exerts drag on the water. The wind energy is transferred from the air to the water, thereby moving the water. There are five large distinct wind-driven elliptical currents called gyres. The Pacific and Atlantic Oceans both have two gyres, one in the north and one in the south in each ocean. The Indian Ocean also has its own distinct gyre. The gyres in the northern hemisphere rotate in a clockwise direction while the ones in the southern hemisphere rotate in a counterclockwise direction due to the Coriolis force of the Earth's rotation. Other major factors influencing ocean movement include tides and the energy caused by seismic events (Kershaw & Cundy, 2000).

The ocean's properties also restrict the transmission of electromagnetic waves, including visible light. During dawn and dusk, when the suns rays approach the ocean surface at a low angle, much of the light is reflected and does not penetrate the water. In midday, light does penetrate the water, but with increasing depth, more and more sunlight is absorbed. The absorption of sunlight varies with wavelength. Wavelengths at the higher end of the light spectrum (yellows and reds) and at the very low end of the spectrum (violets) are absorbed closer to the sea surface. In

contrast, mid-range wavelengths penetrate deeper into the ocean. With light detecting instruments, light can be detected as far as 600m in clear waters, but due to particulates in the water, the amount of useful light is limited to the upper 100m of water (Garrison, 2007).

Water particulates can greatly alter the amount of light available underwater. Particulates scatter light as it enters the ocean, causing decreased visibility. In clear conditions, divers have reported being able to see as far as 200m. In shallow coastal waters, due to turbidity, the amount of useful light available for vision is often so poor that divers cannot use any visual signals at all (Kinney, Luria, Weitzman, 1967).

The inability of electromagnetic waves to propagate well through water imposes both large restrictions for human vision and severely limits the communications possibilities underwater. The absorption, reflection and refraction properties of water cause light energy to fade and scatter, preventing the use of traditional light-based methods of transmission (Chitre, Shahabodeen, & Stojanovic, 2008; Pompili & Akyildiz, 2009; Quazi & Konrad, 1982; Stojanovic, 2006). As a result, acoustic-based methods are used because sound travels faster in water than in air and propagates well beyond the range of light (Christ & Wernli, 2007). However, even acoustic communications have several significant limitations. Sound travels at a much slower speed than does light and, as a result, the propagation delay of communications is up to five times greater than surface communications. Sound is still subject to frequency dependent propagation loss. Lower frequency sounds (e.g., 100Hz) can travel large distances of 1000km or more, whereas higher frequency sounds (e.g., 1MHz) may only have a range of 50m (Pompili & Akyildiz, 2009). The bandwidth is also dependent on the distance of the transmission due to environmental noise and absorption with greater bandwidth at closer ranges. Acoustic communications is also subject to multipath (reception of a single sound signal from multiple paths), fading, high bit error rates, and occasional losses in connectivity (Pompili & Akyildiz, 2009).

The degree to which acoustic communications are attenuated is dependent on the properties of the water itself (Akyildiz, Pompili, & Melodia, 2004). For example, in shallow waters, acoustic communications are subject to a greater degree of multipath arrivals due to both surface and bottom reflections (Chitre et al., 2008). The temperature, salinity and density of the water can also greatly affect acoustic transmissions. For example, rapid changes in water density known as a pycnocline can trap sounds from penetrating through the denser water, prohibiting sonar and acoustic communications (Christ & Wernli, 2007).

The water's density can also affect the manoeuvrability of the UUV by affecting its buoyancy. UUVs are typically positively buoyant to allow them to surface if power or communications problems occur. The composition of the water determines the level of ballasting needed to achieve the appropriate buoyancy before the UUV is launched. Sudden changes in density can affect the movement of the vehicle and in some extreme cases, prohibit the vehicle from moving through the water (Christ & Wernli, 2007). Vehicle navigation and movement can also be greatly affected by ocean currents. The movement of water driven by the wind on the surface or changes in density in deeper waters can shift the vehicle back and forth, affecting its stability. In particular, UUVs have difficulty traversing through the turbulent surf zone and shallow waters where high winds and strong waves prevent most vehicles from operating (Consi et al., 2010).

In sum, the ocean imposes a number of challenges for operating underwater vehicles. Many of these challenges extend to the human operator who is required to adapt and operate the vehicle in an environment that limits perception, communications, and the ability to effectively navigate and control the vehicle. In general, these human factors challenges can be divided into two broad categories, problems with teleoperation and problems with supervisory control. Problems with teleoperation are primarily associated with remotely operated vehicles (ROVs) that require manual control, whereas problems with supervisory control are primarily associated with autonomous underwater vehicles (AUVs). ROVs and AUVs make up the two most common types of UUVs used today. In the next section, these two vehicles types are discussed in more detail because of their popularity and their foreseen use within the CF.

3 Unmanned Underwater Vehicles (UUVs)

UUVs are a special class of unmanned systems specifically designed for underwater use. UUVs are typically used to collect oceanographic data and perform tasks that might otherwise be impossible or dangerous for humans. UUVs provide means of entering an inhospitable environment and offer the capability to explore even the deepest parts of the ocean. UUVs have become essential tools for operating under dangerous conditions or for extensive periods of time. UUV technologies continue to evolve and their potential is growing. UUVs range in shape and size, depth ratings, payload, navigational capabilities, and their control method.

The main objective of this section is to provide a brief overview of two broad categories of UUVs introduced in Section **2**, ROVs and AUVs. While other types of unmanned maritime systems exist, such as remote surface vehicles, bottom crawlers, and hybrid underwater vehicles, ROVs and AUVs in particular are discussed in greater detail because of their prevalence and increasing use in military operations.

3.1 Remotely Operated Vehicles (ROVs)

In the maritime world, the term remotely operated vehicle or ROV specifically refers to a UUV that is controlled by a human operator from the surface. The control interface is directly connected to the ROV through a group of cables called the umbilical cable (commonly referred simply as the umbilical or tether) that transmits of power and communications to the surface. *Figure 1* shows examples of two of the CF's current ROVs, the Deep Sea Intervention System (DSIS) and the Phantom ROV.

Figure 1: The CF Deep Sea Intervention System (DSIS) ROV (left) and the CF Phantom ROV (right).

The main advantage for using ROVs in place of divers is their ability to descend to greater depths and operate for longer periods of time underwater. For example, the Jamstec ultra-deep Kaiko ROV has traveled the deepest part of the ocean, the Marianas trench at 10.91km depth (Christ & Wernli, 2007). ROVs have extended endurance because the umbilical cable allows power to be

transmitted to the ROV for long periods of time. ROVs also have flexibility because the umbilical cable allows for direct control of the ROV by a human operator.

ROVs (or ROV-like devices) date back to the late 1800s, but it was not until 1953 that the first umbilical cable ROV was developed (Christ & Wernli, 2007). Since then, ROVs have evolved significantly. The US Navy is credited for advancing this technology for ordnance removal. In particular, the US Navy's Cable-Controlled Underwater Research Vehicle (CURV) ROV was used to recover an atomic bomb that sank in an aircraft accident in 1966 off the coast of Spain (Christ & Wernli, 2007). As well, industries such as the oil and gas industry have been using and advancing ROV technology to support underwater drilling, observation and construction activities (Westwood, 2010; Whitcomb, 2000).

ROVS are classified into categories based on their size, depth capabilities, horsepower and whether they have an electric or electro/hydraulic power supply. According to the Marine Technology Society, ROVs can be classified into seven groups. *Table 1* provides the breakdown of ROV classes and a short description of each class.

Table 1: Classes of ROVs based on their capability and horse power.

Class	**Capability**	**Power (hp)**
Low Cost Small Electric ROV	Observation (<100m)	<5
Small (Electric)	Observation (< 300m)	<10
Medium (Electro/Hydraulic)	Light/Medium Heavy Work (<2,000m)	<100
High Capacity Electric	Observation/Light Work (< 3,000m)	<20
High Capacity (Electro/Hydraulic)	Heavy Work/Large Payload (<3,000m)	<300
Ultra-Deep (Electric)	Observation/Data Collection (>3,000m)	<25
Ultra-Deep (Electro/Hydraulic)	Heavy Work/Large Payload (>3,000m)	<120

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ROVs can be equipped with various payloads such as object manipulators, video cameras, lights, tools and sensors. ROV payloads might also include a contact temperature (CT) probe, a turbidity sensor, a pressure sensor, a sidescan sonar, an optical camera, a multi-beam echo sounder and a magnetometer. Many ROV systems allow for modular payloads to maximize flexibility (Christ & Wernli, 2007). **Annex A** provides a short list of ROVs on the market today with information on their capabilities and their possible sensors.

The wide variety of payloads has made ROVs particularly advantageous for numerous underwater tasks including underwater search and rescue, bathymetry and oceanographic data

collection, vessel and port inspection, and underwater construction. The wide range of capabilities offered by ROVs has made them vital tools for scientific research, oil and gas exploration, and military applications (Christ & Wernli, 2007). Yet, despite their success, ROVs still have some key limitations stemming from the umbilical cable and from the need for a human operator.

The tether can be very cumbersome when operating the ROV. It can become tangled or snagged, hindering the movement of the vehicle. It can also create significant drag in the water, which limits the vehicle's speed and efficiency in the water (Christ & Wernli, 2007). The human operator must always manage the umbilical cable for entanglement, and control the tautness of the umbilical cable while the ROV moves. The need for a human operator itself can be problematic for some tasks. Long endurance and repetitive tasks are difficult for human operators from a vigilance standpoint (Warm, Parasuraman & Matthews, 2008). Thus, for long endurance tasks, particularly in deep water, AUVs have grown in popularity because they eliminate the need for both the umbilical cable and the human operator.

3.2 Autonomous Underwater Vehicles (AUVs)

Like ROVs, an AUV is an underwater robot primarily used for sensing and capturing data from the underwater environment. The key factor differentiating AUVs from ROVs is system autonomy. That is, AUVs can be programmed to swim pre-programmed missions, collect data and return to a recovery location without human control. AUVs are also untethered and they communicate with the surface through wireless underwater communications. AUVs are monitored from the surface using a monitoring interface which can provide basic vehicle health status and navigational information (*Figure 2*).

Figure 2: The Explorer AUV developed by International Submarine Engineering Ltd used for Project Cornerstone to map the Canadian Arctic sea floor.

AUVs are still regarded as a relatively new technology. While some consider torpedoes the original AUVs (Blidberg, 2001), what is regarded as an AUV today was first developed just prior to the 1970s; these AUVs were very specialized and few were ever used for long periods (Blidberg, 2001). In the 1970s, some universities began to build testbeds for AUVs (Blidberg, 2001). AUV technology did not make any significant gains until computer hardware and software technologies advanced to a point where sufficient intelligence could be built into the vehicle to allow for autonomous operation. Between 1983 - 1985, the first commercial AUV was developed and approximately 75% of the AUVs on the market today were built between 2001 - 2005 (Westwood, 2010). A recent survey of AUVs recorded 629 units available as of 2009 (Westwood, 2010). The growing popularity of AUVs has largely been the result of the growing search for oil,

the scientific exploration of our oceans, and the military desire to have unmanned systems integrated into their future capabilities (Westwood, 2010).

The key attraction to AUVs over ROVs is their ability to operate autonomously for many hours with little human intervention. AUVs can operate from hours to days at a time (Blidberg, 2001). Underwater gliders, a special class of AUVs, can operate for weeks before their energy stores are exhausted (Bachmayer et al., 2004). But very few AUVs today are truly autonomous. While they can be pre-programmed to follow a particular route and return, today's AUVs are unable to dynamically alter their program, avoid unforeseen obstacles, and navigate with precision. These problems continue to be a challenge for future AUV autonomous development (Blidberg, 2001).

For AUVs to be truly autonomous, three different types of autonomy need to be achieved: decision autonomy, navigation autonomy and energy autonomy. Decision autonomy refers to the AUV's ability to appropriately sense, interpret and react to changes in the environment and to changes in the mission. Navigation autonomy refers to the ability to navigate, avoid objects, and find alternate routes to meet mission goals. Energy autonomy refers to the ability of the AUV to use a reliable low-powered energy source, with the possibility of knowing when and how to recharge this source, so that it can operate for long endurance missions (Hagen, Hegrenaes, Jalving, & Midtgaard, 2009).

Because global positioning system (GPS) cannot be used underwater for navigation, AUVs rely on several different technologies to navigate. AUVs can estimate position using various methods such as long baseline (LBL) sonar, short baseline (SBL) sonar or ultra short baseline (USBL) sonar. These methods require the use of transponders on the seafloor to triangulate the position of the vehicle. Doppler velocity log (DVL) is also used and it applies sound to reflect off the seafloor or sea layer to estimate a vehicle's velocity. A more sophisticated and expensive method is the use of inertial navigation systems (INS) to calculate position, velocity and attitude. This method uses data from accelerometers and gyros to measure change in attitude, depth and velocity. These measurements use two or more external beacons to estimate the vehicle's position. Unfortunately, navigation with INS alone will still lead to errors in position over time. Thus, other sensing data are used and mathematically integrated with the INS through a Kalman filter (Hagen et al., 2009) to better estimate position. AUVs are generally not capable of navigating through highly cluttered areas and they do not have the capability of real-time control over precise navigation. However, they are extremely useful when navigating through deep waters (greater than 200 feet) and gathering data for extended periods of time (Hagen et al., 2009).

The sensors used to collect data from AUVs are limited by the same problems of underwater electromagnetic wave absorption, reflection and refraction. To compensate, acoustic methods of data transmission are preferred. While optical cameras can be used to provide some short range video images, acoustic sonar has become the most important tool for underwater sensing. Sensor platforms on AUVs commonly consist of some form of active or passive sonar (e.g., multibeam and narrow beam sonar, sidescan sonar) and optical cameras (e.g., 35mm cameras, high-definition television (HDTV) cameras). Laser range finders, hydrophones and magnetometers are also occasionally used (Whitcomb, 2000).

The current capabilities of AUVs and their sensing systems allow for a more comprehensive picture of the underwater environment than previously possible. Today, AUVs are increasingly

common and are highly functional systems. **Annex B** provides a list of present day AUVs and their capabilities. It is foreseen that AUVs will play an increasing role in the future of the CF and other militaries (CF, 2011; US Navy, 2004). In the CF, ROVs are already used to aid operations such as search and rescue. For example, the CF's DSIS ROV took part in the search and recovery operations of Swissair Flight 111 which crashed off the coast of Peggy's Cove, Nova Scotia in 1998 (Transportation Safety Board of Canada, 1998). According to the CF's strategic document, Leadmark: The Navy's Strategy for 2020, there are several operations that will be critical to the future CF Navy and all can benefit from UUVs: (a) Command, Control, Communications, Computers, Intelligence Reconnaissance and Surveillance (C4ISR) (b) anti-submarine warfare (ASW) and (c) MCM (Canada, 2001).

In C4ISR operations, UUVs can operate for long durations acquiring information and intelligence. C4ISR is also integral to ASW for providing a complete picture of the underwater battlespace. Canada's ASW strategy involves a layered approach to defence and is foreseen to contain both manned and unmanned assets undersea and in the air. At its outermost layer, in open waters, ISR capability allows for underwater detection of threats before the threats actually enter Canadian waters. At the intermediate layer and inner most layers, assets including UUVs might be required to detect, localize and potentially engage targets (Canada, 2001).

The primary use for UUVs in the future of the CF will be for MCM operations. MCM refers to all techniques used for responding to sea mine threats (CF, 2011). Similar to how UGVs play an important role in responding to land mines, UUVs can be deployed to detect, identify and dispose of sea mines.

4 UUVs in MCM Operations

One of the most common threats in current warfare, both on land and underwater, are man made mines and explosive ordnance devices. Mining offers a remote attack possibility, is a force multiplier, and provides a long term threat. Mines are a weapon of position, they are cheap, easy to produce, simple to lay, and as such are an ideal weapon of choice for terrorists and criminals (CF, 2011). In offensive mining, mines are normally placed where ships must or will travel, at choke points and approaches to harbours. When used in defence, mines are usually placed in wide fields across likely approach routes for hostile maritime forces. MCM are thus considered an essential and necessary capability for force protection in both land and maritime environments. The varieties of sea mines are depicted in *Figure 3* illustrating the extent and diversity of the threat.

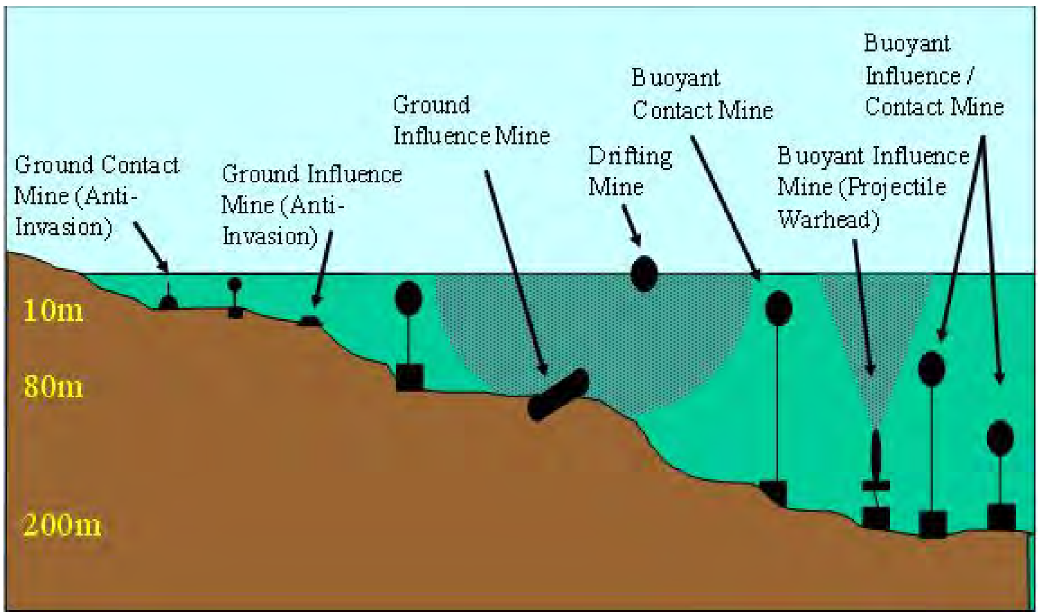

Figure 3: A variety of mine types that can be encountered in a littoral environment.

MCM include all measures taken to reduce the risk of damage to ships or injury to personnel from mines (CF, 2011). The best approach to reducing risk is locating and avoiding the mine(field)s. Failing the possibility of avoidance, measures to neutralise the effect of mining are taken. Based on the nature of the threat and the mission at hand, several MCM techniques have evolved over time that can be categorized under three categories: passive MCM, self-protective measures (SPM) and active MCM.

Passive MCM are considered an indirect measure that utilizes channelization as a means of threat avoidance. Channelization is accomplished by establishing narrow routes for ships to follow, limiting the amount of sea area where ships may encounter mines (i.e., Q-routes). An important component in passive MCM is route survey. A route survey is a survey of existing shipping routes and areas to compile a database of existing seabed objects. Route surveys are time and resource consuming, but are a necessary component in mine avoidance (CF, 2011).

SPM are those undertaken by individual ships for their own risk reduction. Tactical SPM entails careful ship-handling to reduce the ship's influence signatures. Material SPM utilize equipment or materials to reduce this risk, in the form of electro-magnetic signature suppression, acoustic signature control, mine avoidance sonar, electro-optical devices or shock hardening (CF, 2011).

Active MCM include minehunting, minesweeping, and clearance diving. Minehunting involves using sonar to search the sea for mines with the goal of detecting them before they are actuated. Minesweeping involves the towing of devices that are intended to physically disable the mines or simulate ship signatures to induce mine explosion. Different types of sweeping include mechanical (e.g., wire sweep), pressure and influence sweeping. Clearance diving is a specialized form of diving specifically developed to allow close approach to influence mines. It is currently the most effective method of minehunting in confined waters and the only method for mine recovery and exploitation during CF operations (*Figure 4*) (CF, 2011).

Figure 4: Life support and personal protective equipment for CF divers.

Clearance diving is personnel intensive, is resource and time consuming, and requires numerous safety measures to be in place. In the CF, diving is usually conducted in pairs and divers are tethered by a lifeline to the surface vessel. The lifeline supplies the gas mixture for breathing, is used as a depth gauge, and provides a means of communication both to the surface and to the fellow diver. Adverse environmental conditions such as sea state, currents, and tides can limit divers' mobility and navigation during search. Navigation is usually provided by the surface personnel, who direct/guide the diver to the inspection point by pulling on the lifeline, although an underwater compass may be used in some cases. Once at the inspection site, the turbidity or high clutter of the seabed can severely reduce the visibility and make threat assessment more difficult and dangerous for the diver. This is especially the case in shallow water and confined spaces such as in jetty searches. Divers rely on hand-held sonar for target classification, but on occasion may resort to haptic means, carefully collecting information using heuristics such as average arm length. Once the threat has been classified, the diver returns to the surface with the information that is then used to identify the type of mine, which will determine how the mine will be neutralized. The diver is further responsible for delivering and correctly placing the appropriate charge at the mine site.

It is evident that current conduct of MCM in CF holds many hazards for clearance divers, despite the safety measures employed. Consequently, a great deal of effort has been put into using UUVs to perform aspects of MCM. UUVs are particularly apt for performing route surveys and mine hunting tasks. An AUV can be pre-programmed along a planned route to gather sea data. In addition, sidescan sonar can be used to visualize the sea floor. A sonar operator aboard a surface ship scans the sidescan sonar imagery for a potential target. If a target is detected, a marker is thrown in its vicinity and a diver is deployed to determine whether or not the target is an actual mine threat. The diver is equipped with a handheld sidescan sonar that he uses to examine the target. If the target is classified as a mine, a specialized UUV colloquially called a “one-shot” or “single shot” disposable system can be used in mine disposal. They are low-cost and expendable UUVs, intended for one-time use. The role of a “one-shot” UUV is to manoeuvre close to a mine and self-detonate, exploding the mine along with it. In this example, different UUVs are used for a “dull” (i.e., detection) task, reducing the number of resources required; and a “dangerous” (i.e., mine disposal) task, reducing the risk to the diver.

With the increasing use of UUVs in the military and other industrial operations, it is surprising that there is little so information on the human factors issues associated with the use of UUVs. While a great deal of human factors research has been dedicated to UAVs and UGVs, UUVs have been relatively ignored, despite the fact the underwater environment, the control environment, and the missions performed in the water are distinctively different from missions in the air and on the ground. In the next section, we discuss several human factors issues associated with UUV usage.

5 Human Factors Issues with Operating UUVs

Human factors issues related to unmanned air and ground vehicles have been well-documented (Chen et al., 2007; Cooke et al., 2006). In particular, the high rate of UAV crashes has led to much research on remote operator control of UAVs (Williams, 2004). Perceptual issues are also a problem for both UAVs and UGVs, whereby the human operator is removed from the immediate operational environment. Thus, the operator is deprived of sensory cues, but must make navigational and control movements, and mission-related decisions based on sensor imagery that can lack resolution, color, field of view, and depth cues (McCarley & Wickens, 2005). Even when vehicles operate autonomously with a human operator performing only a supervisory role, human factors issues arise related to an unbalanced workload and low SA (Cummings & Guerlain, 2007). Automation reliability (Dixon & Wickens, 2006) and trust issues resulting from unreliable automation have also been investigated (Ruff, Narayanan, & Draper, 2002).

While, to the best of our knowledge, there is no documented evidence of the frequency of UUV failures and accidents, it is well known that ROV control and umbilical cable entanglement are problematic (Christ & Wernli, 2007). Moreover, AUVs have been reported lost at sea due to system failures (Meng & Qingyu, 2010). A number of system failures can occur with AUV operation, including sensor failure, blocked or flooded thrusters, lost or stuck fin, rotor failure, and hardware / software crashes (Antonelli, 2006; Giger, Kandemir, & Dzielski, 2008). Meng and Qingyu (2010) estimate that the root cause of lost AUVs result from errors due to manufacturing (52%), maintenance (25%), AUV design (14%), operations (7%), and external factors (2%). To date, the role of human factors in UUV mishaps is unknown.

Based on research conducted on air and land unmanned systems, it is conceivable that human factors can play a role in UUV problems. A number of human factors issues are common to all types of unmanned systems, but in some cases, these problems are likely magnified by the challenges of operating underwater. In fact, because operating in the underwater environment is so challenging, we hypothesize that operating UUVs will present new human factors challenges not present in surface unmanned systems. For example, SA issues for the human operator controlling or supervising a UUV can be far greater than surface and air unmanned systems due to the constraints on perception and the restricted communications available underwater. In the subsequent section, a number of human factors issues when operating UUVs are discussed. The topic of operator perception will begin our discussion, followed by issues related to operator control of UUVs, the UUV control station and interface, SA and workload issues, and trust issues related to automation failures.

5.1 Perception in the Underwater Environment

It has been well established that human perception underwater is significantly degraded. The diver’s vision is compromised by the lack of light, particles in the water and a restricted field of view. Tactile sense is impaired by the temperature, the water pressure and density, and the dive suit (Shilling, Werts & Schandelmeier, 1976). Similarly, an operator operating a UUV faces similar challenges due to a lack of sensory cues in the operating environment. The operator’s awareness of the underwater environment is dependent on a video camera image, a sonar image, sensor indicators, and a physical model of the operating area (Lin & Kuo, 1997).

The UUV video camera may have a low resolution, a reduced field of view, and delays in video transmission (Brayda, Ortiz, Mollet, Chellali, & Fontaine, 2009; Lin & Kuo, 1997). The lack of light and high turbidity underwater affects the image on the operator's video monitor. At times, high turbidity is caused by the UUV itself, as its thrusters stir up sediment on the ocean floor. Because wavelength absorption occurs as a function of water depth and turbidity, the color of objects may appear altered (e.g., blues may appear green) (Kinney, Luria, Weitzman, 1967). While ROVs are equipped with lights to accommodate the dark environment, particulates in the water can cause significant backscatter, reducing visibility. When viewing images on the UUV monitor (see example of ROV image in *Figure 5*), the operator relies solely on pictorial cues for depth perception, but underwater, there is a general lack of visual stimuli to generate depth cues (Shilling et al., 1976). As a result, in some circumstances, depth perception can be even more impaired relative to unmanned surface or aerial vehicles.

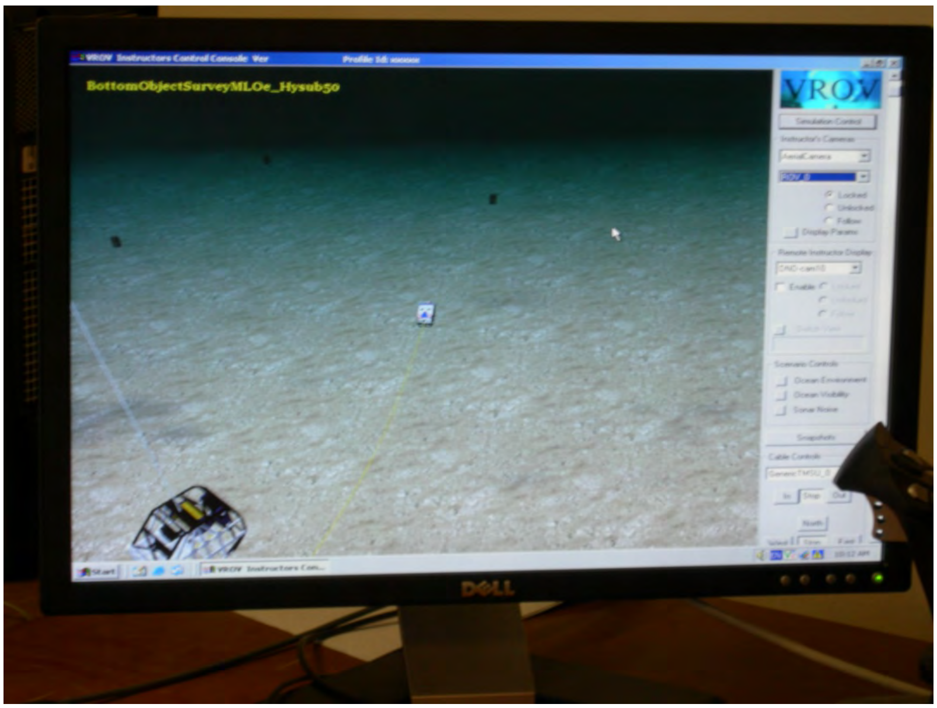

Figure 5: A simulated ROV video camera image

Recent research suggests that even the camera's viewpoint can alter the operator's performance and perception of the environment. Brayda et al., (2009) examined the effect of camera viewpoint on operator ability to navigate a UGV on pre-determined paths. They found that the higher camera viewpoints (i.e., cameras positioned higher from the ground) resulted in greater path deviations than lower viewpoints (i.e., cameras positioned lower to the ground). In addition, some participants did not recognize previously driven paths when the camera viewpoint was changed.

To supplement video images from a camera, sonar is commonly used to expand the viewing distance. However, unlike a video display, sonar displays require training to read. The images are commonly low in resolution, are jagged and lack fine detail, color, and depth. Moreover, the sonar image is affected by movement. Objects that absorb sound will not appear on the sonar and smooth surfaces might provide a very strong signal in one direction, but virtually no signal in

another. Image quality can be improved by using a high frequency sonar (e.g., 700kHz), but there is a trade-off between better image quality and range of the sonar.

Poor vision and poor depth perception restrict an operator's ability to perform a number of tasks including the ability to navigate, manoeuvre the vehicle, detect objects in the environment or handle objects. Poor visual perception can also result in accidents, and incidents can be frequent, resulting in increased costs, lost time and damage to the robot. In fact, some ROVs are enclosed within a protective shield just to guard the robot from frequent contact with obstacles and debris. Again, poor navigation is not solely due to perceptual issues. The control station and the underwater environment itself present complexities that make it difficult to navigate and manoeuvre the vehicle.

5.2 UUV Control and Displays

Navigating and manoeuvring a ROV is a difficult task. Aside from the visual limitations discussed in Section **5.1**, the operator must control the robot along six degrees of movement freedom: surge (forward/backward), heave (up/down), sway (left/right), pitch, roll, and yaw. At the same time, the operator must also attend to the vehicle's velocity, altitude, and position in the water. Water currents continually apply force to the vehicle such that the operator must constantly make small positional and attitude adjustments to compensate. In addition, the vehicle's buoyancy and the occasional contact with debris can also affect the manoeuvrability of the ROV (Christ & Wernli, 2007). While manoeuvring the ROV, the operator must concurrently also manage the umbilical cable, to allow the ROV to move as required, by providing it with just enough slack to allow the vehicle to move freely, but also to limit umbilical cable entanglement. Poor umbilical cable management can cause significant drag and affect the vehicle's performance (Zand, 2005).

The task of maintaining an ROV's correct attitude and estimating the location of objects around it is difficult. Through the ROV's control interface, the operator must gather spatial information about its attitude (i.e., its body axes) and position with respect to the seafloor, the sea surface, and objects in the environment. This is a complicated task because the operator must adopt a vehicle-centric frame of reference as if it were his or her own egocentric frame of reference which increases cognitive demand (Taylor & Rapp, 2004).

The problem is further compounded by the fact that the ability to estimate egocentric orientation when underwater is degraded. That is, when an ROV operator adopts a vehicle-centric frame of reference and the ROV is underwater, the operator will experience degrees of error in estimating its egocentric orientation depending on its actual pitch underwater. This degradation in estimating egocentric orientation has been studied in divers. When divers are in the water with their head up, their egocentric orientation error is approximately 7 degrees. When divers are in the water, in a head down position, their egocentric orientation error increases to approximately 30 degrees (Shilling et al., 1976).

The loss of one's own egocentric orientation is problematic for overall spatial awareness because we use our own egocentric orientation to judge the relative position of the objects around us. For example, when individuals are asked to imagine themselves in a room either standing upright or reclined and then identify where objects are in the room, their response times will vary depending

on how they imagine their posture. When standing upright, participants have faster response times with objects relative to their head and feet. However, while reclined, objects to the front and back are responded to faster (Tversky, 2003). This situation is similar to an ROV operator who must cognitively represent the ROV's posture or attitude and estimate the location of objects around it. The operator's ability to easily and accurately adopt the ROV's frame of reference will have strong implications for overall spatial awareness.

To examine the role of the interface in understanding attitude and spatial awareness, Donovan and Triggs (2006) investigated two different ROV interfaces, Inside-Out displays and Outside-In displays, and measured their effects on spatial awareness of attitude and control errors when operating an ROV. Inside-Out and Outside-In displays differ in their frame of reference. Inside-Out displays are egocentric, showing the vehicle as a fixed object, with the horizon moving around it. Outside-In displays are exocentric, shows the vehicle moving around a fixed horizon. Both types of displays are used in aviation, but most aircrafts use Inside-Out displays despite the fact that some research has shown that Outside-In displays are more intuitive. Donovan and Triggs (2006) found that, while both display types were superior to having no such display, the Outside-In display was superior in a number of spatial measures suggesting that it provided the most effective means for operators to easily interpret spatial information. These findings demonstrate the importance of having a well-designed operator interface in conveying spatial information for UUVs.

In addition to problems with attitude, operators also have difficulty navigating ROVs through space. Similar to evaluation of space around one's body, moving through space requires an individual to navigate relative to a frame of reference. For large spaces, salient landmarks are used to organize space (Tversky, 2003). ROV operators are trained to do exactly this. Prior to entering the water, ROV operators are encouraged to obtain a good understanding of the underwater environment and to develop and maintain a mental map of this environment (Martin et al., 2005). However, frequently there is little or no information of the environment available beforehand. Sonar is also used to initially navigate the ROV to a destination and then switch to visual means for a more detailed investigation. Once on site, a visual search can be performed using the ROV's optical camera. A visual search requires the operator to define a reference point and maintain visual contact with the reference point to maintain orientation. If the site is featureless and no reference point can be used, sonar navigation is preferred. Sometimes, grid searches are performed. Similar to techniques used by divers, the ROV would follow a pre-determined grid path by following visual or sonar markers that are placed on the sea floor prior to the grid search (Christ & Wernli, 2007).

The ROV operator controls the ROV using a control station (*Figure 6*). Control stations can vary in size, complexity and location. Some ROV control stations are placed in containers while other systems are simply desktop personal computers (PCs). Some are portable and allow the operator to use the system from a small boat. Therefore, at one extreme, the operator can reside in a comfortable office-like environment, while at the other extreme, the operator can be controlling the vehicle outdoors, in a small boat, with waves splashing over the side (Christ & Wernli, 2007). Each type of control station may have unique human factors issues associated with it.

The technology behind UUVs has improved dramatically over the last three decades. However, the operator interfaces and controls have remained relatively unchanged since the 1970s (Martin et al., 2005). Generally, ROVs controls include a joystick, trackballs, and hard-coded buttons and

dials. There may also be software controls and specialized controls for devices like manipulators. The control station may allow for both gross and fine control of the vehicle. Typically, an operator may want more fine control if the ROV is in a confined space or if the ROV is working in an environmentally sensitive site. If fine movement control is not available, a small shift in the operator's joystick could send the vehicle colliding against a wall and damage the vehicle (Christ & Wernli, 2007). Typical displays include a forward camera view from the UUV, sensor displays, map displays showing the waters where the UUV is traveling, and status displays showing information regarding the UUV's health indicators.

Figure 6: An ROV control station

It is unknown to what extent UUV developers have incorporated human factors and usability methods in the design of UUV control interfaces. There is ongoing work to improve portions of the interface to aid depth perception with stereovision (Jeon, Lee, & Lee, 2001; Negahdaripour & Firoozfam, 2006; Woods, Docherty, & Koch, 1994), to deal with increasing autonomy (Garcia, Fernandez, Sanz, & Marin, 2010), to help build trust in UUVs (Johnson, Patron, & Lane, 2007), and to provide a more intuitive interaction for the operator (Garcia, Prats, Sanz, Marin, & Belmonte, 2010). Future UUVs will be more autonomous, their tasks may require the fusion of more data and time sensitive responses and actions, communications may allow for real-time feedback, and one operator may be responsible for several UUVs at a time. If these predicted changes do occur, UUVs will require new paradigms in interface design to accommodate not only issues related to perception, control, and navigation, but also problems associated with greater degrees of automation such as SA and workload.

5.3 Situation Awareness and Workload

A great deal of research has been dedicated to SA and workload issues with operators using unmanned systems. For UAVs, mishaps tend to occur during take offs and landings (Williams, 2004) and are associated with periods of high workload (Thompson, Tvanyanas, & Constable, 2005). Similarly, it is suspected that when controlling an ROV, high workload conditions would likely arise in situations where the operator must perform complex and stressful tasks, such as handling sensitive objects with a manipulator arm. For example, a potential future military application for ROVs may be battle damage repair or ordnance removal from underwater structures. In this case, the operator must focus on the main task of manipulating the object (e.g., a sea mine), while at the same time, constantly adjusting the position of the vehicle, and attending to other subsystems such as the umbilical cable, ROV health indicators, and sensors.

For today's AUVs, there is little SA of the vehicle's health, position, and mission performance. Real-time, high bandwidth transmission of AUV data is currently technologically difficult due to communications limitations in the water (Akyildiz et al., 2004). As a result, the information transmitted by an AUV might be as simple as a "heartbeat" to indicate that it is operating. Some AUVs will send positional information, but the accuracy of the information can be unreliable and the transmission might be delayed by many seconds.

However, there are several reasons to believe that this may change in the future. First, the ongoing advances in underwater acoustic communications will eventually allow for information to be delivered faster and with greater reliability (Akyildiz et al., 2004). Second, UUVs are expected to take on a greater role in military applications including missions that are time-sensitive and require complex coordination. For example, according to the US Navy's UUV Master Plan, it is predicted that UUVs will one day be weaponized and will play a role in time critical strikes against adversarial targets (US Navy, 2004). Third, UUV developers are continually improving the automation and autonomy of UUV systems (Hagen et al., 2009). While improved automation and autonomy can eliminate some problems related to workload, it can be expected that operators will encounter increased SA issues because the human is further removed from the loop (Ruff et al., 2002). Finally, there is a trend in research towards using swarms of AUVs in future underwater applications such as using multiple AUVs to establish an underwater communications and navigation network (Bean et al., 2007). The monitoring and coordination of multiple AUVs with one operator could be especially hazardous from a human factors standpoint if there are little improvements to underwater communications and AUV navigation. The operator would have a higher degree workload while his/her SA of each AUV's position would continue to be delayed and possibly inaccurate.

The effects of having a single operator monitor multiple unmanned systems have been investigated for UAVs. Cummings and Guerlain (2007) conducted a study where a single operator had to monitor and reallocate multiple missiles to targets in a simulation environment. They found that as the number of missiles increased, SA performance degraded, demonstrating the dangers of having a single operator control multiple vehicles. Ruff et al., (2002) reported similar results regarding SA, but also found that the relationship between the number of UAVs being monitored and the level of automation (LOA) had a more complex affect on SA and workload.

Ruff et al., (2002) had participants monitor one, two or four UAVs under three different levels of automation: manual control, management by consent (the automation asks the operator for permission to execute a task), or management by exception (the automation does not ask for consent and will proceed unless the operator makes specific commands to override the automation). Their results showed that workload was the lowest when the operator had to control only one vehicle under manual control and workload increased monotonically as a function of the number of UAVs under both manual control and management by consent. However, under management by exception, workload remained relatively constant. SA decreased monotonically as a function of the increasing number of UAVs for all three levels of automation, but in this case, both manual control and management by exception had the highest levels of SA, particularly when four vehicles were being monitored. When the UAVs were controlled under management by consent (i.e., the highest LOA), SA was the lowest relative to the other LOAs (Ruff et al., 2002).

SA and workload concerns for operators also arise when highly automated and autonomous systems fail. If one AUV in a swarm were to fail, the operator might be tasked to quickly troubleshoot the problem, retask the other vehicles to help, or the operator may have to find other alternatives to achieve a mission (Giger et al., 2008). Automation failures also impact the trust that the operator has in the system. If an operator’s trust in the UUV degrades, it can significantly alter his or her workload and monitoring strategies and can result in rejection of the technology.

5.4 Trust in UUVs

The topic of trust in highly automated and autonomous systems is complex. Too little trust in automated systems results in a higher degree of system supervision, thereby resulting in higher workload for the operator, and at times, complete disuse of the technology. In contrast, too much trust in automated systems results in complacency errors, decision biases and loss of SA (Lee & See, 2004; Parasuraman & Riley, 1997).

Again, researchers have examined how automation failures affect trust in UAVs. Ruff et al., (2002) found that automation reliability interacts with the number of UAVs and the LOA to impact the trust in the automation. In general, when the automation reliability was not perfect, trust increased as a function of the number of vehicles for manual control. However, the opposite effect occurred for higher levels of automation. That is, trust decreased as a function of the number of vehicles in the management by consent and exception conditions (Ruff et al., 2002).

The study by Ruff et al., (2002) demonstrates how even highly reliable but not perfect automation can impact how operators use automation. Similar to the work on UAVs, we expect that automation failures will impact the trust that the operator has in the UUVs. A key difference between UAVs and UUVs is the operating environment. Given the harsh conditions of the underwater environment which exposes mechanical and involved electrical equipment to fouling and corrosion, and the slower and less reliable methods of communications, we can expect higher levels of UUV failure which will impact the trust of the operator. At least two issues are at the forefront of current research on trust in UUVs. The first issue deals with trust in an associated UUV technology, automated target recognition (ATR). The second issue deals with trust in mission planning and methods to communicate autonomous actions to the operator.

In the military, the predominant use for UUVs in the future will be in MCM related functions (CF, 2011; US Navy, 2004; Withington, 2010). In MCM, AUVs are commonly tasked to perform route surveys of the seafloor for mine-like objects using sidescan sonar. To improve the detection and classification accuracy of mines, military organizations, including the CF, are experimenting with ATR technology (Myers, 2009). ATR utilizes a computer decision algorithm for detecting and classifying mine-like objects from a sidescan sonar image. For instance, the algorithm could work by automatically measuring an object's project acoustic shadow(s) to infer the object's size and shape, which can then be compared to known target types and then classified as mine-like or non-mine-like (Myers, 2009). When the algorithm detects and classifies an object as mine-like, it will direct the operator's attention to the object by visually cuing the object in question. The operator then decides whether the object warrants further investigation or not. The algorithm is not perfect and produces a high number of false alarms (Kessel, 2003, 2005). Sonar operators have low trust in ATR systems and regard them as more of a burden than an aid because of the high number of false alarms produced (Kessel, 2003, 2005; Kessel & Myers, 2005). Presently, DRDC is looking at methods to improve trust in ATR, by improving the algorithm and by altering the way ATR is implemented and used by the operator.

Trust will also be important when monitoring a swarm of highly autonomous AUVs to perform a mission. Prior to the execution of the mission, a mission plan must be developed to identify the tasks involved and the dependencies that exist between the tasks (Johnson et al., 2007). During a mission, however, circumstances are likely to arise that will require the AUVs to alter their initial plan. The AUVs must be able to adapt successfully to dynamic changes during the execution of the plan or risk mission failure. For the operator who is in charge of monitoring the AUVs, he or she must sufficiently trust the AUVs to act autonomously and adapt to changes but must not become so complacent that he or she is unaware of vehicle failures if they do occur.

Johnson et al., (2007) are currently developing a novel interface framework to address the issue of trust in a multi-AUV scenario. Their objective is to provide usable information to the operator, without providing too much irrelevant information, regarding the state and actions of each individual AUV in a swarm scenario. By doing so, they hope to provide SA of the AUVs' autonomous decisions to the operator while allowing the operator the ability to replan AUV missions when necessary. The interface will allow the operator to query the system about the status of the AUVs and will communicate this information to the operator using rules of human-computer etiquette (Parasuraman & Miller, 2004). Through natural and intuitive communication, Johnson et al., (2007) hope that this interface will instill greater trust in the AUV's ability to complete assigned missions.

Methods to improve the communication between the remote operator on the surface and the UUV continue to be a challenge; another challenge is providing a means for communication between divers and UUVs in the water. In the future, simultaneous operations between robots and divers may become more common, thus the need for divers and robots to communicate underwater will be paramount to successful missions. However, both technical and human factors challenges must be overcome before communication becomes effective.

5.5 Underwater Human Robot Interaction and Communication

Due to current safety concerns with actuating sea mines, CF divers are not permitted to simultaneously operate with UUVs. However, future operations could potentially involve divers working side by side with UUVs to perform less dangerous tasks such as ship husbandry and hull inspection. In fact, in industries such as the oil and gas industry, simultaneous ROV and diver operations are relatively common (see Rougier, 1990 as an example). In these operations, the ROV can serve as a transport vehicle by carrying equipment to the diver, it can provide support through additional lighting for the diver, it can be used to move or lift heavy objects, or it can allow surface vehicles to monitor diver activities.

In the future, autonomous AUVs could replace ROVs in performing such tasks (MacLeod, 2010), but this will require some method of communication between the divers and the AUVs. Having wireless communication between the diver and the robot is technologically difficult underwater. As mentioned previously, water does not allow for the propagation of electromagnetic waves and as a result, the most effective ways to communicate wirelessly on the surface do not work well in the water. Thus, other methods have been explored. One method utilizes a tether between a diver and the UUV; however, while this would provide an effective means for communications, the limitations are obvious. The diver would only be able to communicate with one robot and the tether would restrict the access, range and manoeuvrability of both the diver and the robot. Wireless acoustic modems can allow for communication over short ranges, but the modems would impact the dynamics of smaller robots (Verzijlenberg & Jenkins, 2010). An alternative approach is to use the robot's optical sensors to read visual inputs from the diver. These visual inputs can be gestures or some other form of visual marker.

Dudek, Sattar, and Xu (2007) conducted two studies comparing the use of ARTag markers and gestural inputs for communicating underwater with UUVs. ARTag markers are fudicial markers consisting of patterns that can be read by a digital camera and associated algorithms (Fiala, 2005). ARTag markers are similar to a two dimensional bar code that can be recognized by image processing software. Gestural inputs are a natural choice for communicating with UUVs since gestures are commonly used in diver communication. Each marker encodes a set of action commands for the UUV to follow. The diver is required to hold the ARTag marker or a hand gesture in front of the optical camera of the UUV which feeds instructions to the robot. In their first study, Dudek et al. (2007) found that when participants performed a secondary task and used a small vocabulary set to communicate, hand gestures were superior to the ARTag system. However, in their second study, the researchers found that when the vocabulary size increased notably, the ARTag system was superior to hand gestures.

While a visual approach to communicating with UUVs has some promise, it also has limitations. The communication method is still only applicable to short range distances and requires the divers to be in the same visual proximity as the UUV. Furthermore, the reliability of such methods is questionable in turbid dark waters. Thus, it is clear that more research and technological advances are necessary to enhance human - robot communication underwater.

6 Conclusion

The advances in UUV technology have allowed for the exploration of the earth's oceans far beyond the limits of human diving. However, the underwater environment still presents a number of challenges (e.g., poor propagation of electromagnetic waves) that extend to problems for the human operator (e.g., poor vision and less reliable communications). In the current paper, five of these human factors issues were identified and discussed: (a) perception in the underwater environment; (b) issues with controlling vehicles and the displays used to monitor vehicles; (c) SA and workload issues related to controlling ROVs and monitoring multiple AUVs; (d) trust in highly autonomous AUVs and associated subsystems; and (e) potential limitations of human-robot communication.

Some of the human factors problems that were discussed dealt with the manual control of ROVs. Perceptual issues arise because the operator has severely diminished sensory input when manually operating an ROV. The operator must manoeuvre, navigate and orient the vehicle using a video monitor. The underwater imagery projected has little to no natural light, is often blurred by turbidity and has little depth or color information. In addition, operator control of ROVs is a complex task. ROVs have multiple degrees of movement freedom and underwater currents are continually shifting the vehicle. The ROV operator must also manage the umbilical cable to minimize drag and avoid entanglement.

Other human factors problems are foreseen to become more prevalent as AUVs become increasingly autonomous. In the future, if a single operator were to be responsible for monitoring a swarm of highly autonomous AUVs, it would not be surprising to encounter SA issues from having the operator out-of-the-loop. Moreover, when automation failures occur, the operator may experience periods of very high workload while trying to troubleshoot the problem to avoid mission failure. Automation failures can also affect the trust that the operator has in the AUVs and their associated systems (e.g., ATR).

Underwater communication poses yet another human factors challenge when using UUVs. As the UUVs' functions become more diverse in the future, it is conceivable that their role will expand to tasks requiring vehicles and human divers to be in the water simultaneously. To date, wireless communication has been achieved through markers and gestures with limited success, and only under ideal environmental condition. Although currently not feasible, emerging technologies may allow for more effective communication underwater to enable human - robot interoperability.

It is expected that the use of UUVs for security and military applications will continue to grow, possibly at an increasing rate. In the CF, UUVs are expected to play a key role in several naval missions, including ISR, MCM and ASW. The clandestine nature in which UUVs travel make them ideal tools for ISR and force protection tasks. In addition, the ability of UUVs to gather information for extended periods of time makes them excellent candidates for MCM route surveys, minehunting, and ASW tasks. In the US, UUVs are anticipated to be used in clandestine, time critical strikes against adversaries, and swarms of UUVs will create mobile underwater networks.

Yet, to date, the human factors work on UUVs has largely been ignored by researchers in the field despite the fact that there are ongoing human factors concerns for other unmanned systems. While

UUVs do share some of the same human factors concerns as their air and ground counterparts, the underwater environment and the technological limitations of operating in it present new and unique human factors challenges not experienced by air or ground unmanned systems. More research needs to be conducted to better understand these issues.

There are potentially other human factors issues not discussed in this paper that may require further investigative attention. For example, there may be issues related to training and selection of operators, or human resources required to maintain, operate, and help with launch and recovery of UUV systems. These issues were not discussed in this paper, but are likely to be other sources of human-oriented problems. In conclusion, it is believed that all of these human factors problems need to be explored in more detail so that solutions to eliminate or mitigate these problems can be developed.

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Annex A Examples of Autonomous Underwater Vehicles

A.1 Heavyweight AUVs

MANTA TEST VEHICLE

http://auvac.org

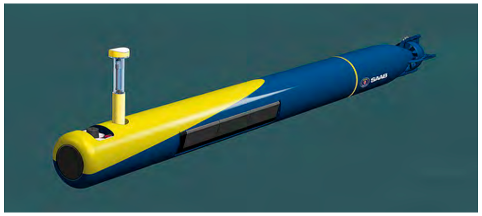
Status:	n/a
Year Launched:	1999
Manufacturer and Product Family:	US Naval Undersea Warfare Center, MANTA Test Vehicle
Depth Rating (m):	800
Standard Sensors:	n/a
Size (m):	10.44 x 4.72 x 1.8
Speed (kts):	10
Battery Life (hrs):	6
Navigation Standard:	n/a

LONG-TERM MINE RECONNAISSANCE SYSTEM (LMRS)

http://auvac.org

Status:	Currently manufactured
Year Launched:	2003
Manufacturer and Product Family:	Boeing Integrated Defence Systems, Long-term Mine Reconnaissance System (LMRS)
Depth Rating (m):	1000
Standard Sensors:	Side Scan Sonar; Forward Looking Sonar
Size (m):	6 x 0.53
Speed (kts):	7
Battery Life (hrs):	n/a
Navigation Standard:	n/a

AUV 62



http://auvac.org

Status:	Currently manufactured
Year Launched:	2003
Manufacturer and Product Family:	Saab, AUV 62
Depth Rating (m):	200
Standard Sensors:	MCM module -Flank Array Sonar -Forward Looking Sonar -Synthetic Aperture Processing; Seabed Mapping Module –MBES; Sub-bottom Mapping -Sub-bottom profiler -MBES; Environmental -CTD sensor -Oxygen sensor
Size (m):	3-7 (optional10) x 0.53
Speed (kts):	10, optional >20
Battery Life (hrs):	Various
Navigation Standard:	GPS; Sound Velocity Meter; Doppler Velocity Log

SEAOTTER MKII

http://archive.auvac.org

Status:	Currently manufactured
Year Launched:	n/a
Manufacturer and Product Family:	Atlas Eletronik GmbH, SeaOtter MKII
Depth Rating (m):	600, 1500
Standard Sensors:	Side Scan Sonar; Sub-bottom Profiler; Multi-beam Echo Sounder; Camera; CTD; Forward looking sonar
Size (m):	3.5 x 1 x 0.5
Speed (kts):	8
Battery Life (hrs):	14 at 4 kts
Navigation Standard:	GPS; Inertial Navigation Sensor; Doppler Velocity Log

ALISTAR 3000

http://www.eca.fr

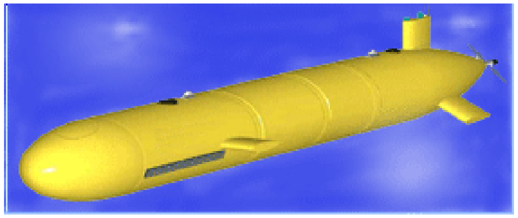
Status:	Currently manufactured
Year Launched:	2004
Manufacturer and Product Family:	ECA Group, Alistar 3000
Depth Rating (m):	3000
Standard Sensors:	Side Scan Sonar; Multi-Beam Echo Sounder; Sub-Bottom Profiler; Camera&Light; CTD Sensor; Sound Velocity Probe; Profiler
Size (m):	5 x 1.45 x 1.68
Speed (kts):	>4
Battery Life (hrs):	24
Navigation Standard:	Inertial Navigation System; Doppler Velocity Log; Altimeter; Depth Sensor; GPS; Obstacle Avoidance Sonar

ECHO RANGER

http://auvac.org

Status:	Currently manufactured
Year Launched:	2004
Manufacturer and Product Family:	Boeing Defense, Space & Security, Echo Ranger
Depth Rating (m):	3050
Standard Sensors:	Multi-Beam Echo Sounder :Kongsberg Maritime EM2000; Teledyne Benthos Programmable Sonar Altimeter (PSA 900)
Size (m):	5.5m × 1.27m ×1.27m
Speed (kts):	7.7 knots
Battery Life (hrs):	28 hours
Navigation Standard:	Ultra Short Baseline; Inertial Measurement; Doppler Velocity Log

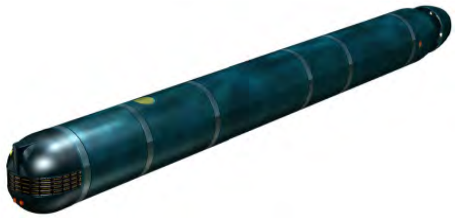
EXPLORER



http://www.ise.bc.ca/explorer.html

Status:	Currently manufactured
Year Launched:	2004
Manufacturer and Product Family:	International Submarine Engineering Ltd, Explorer
Depth Rating (m):	300, 1000 , 3000, 5000
Standard Sensors:	Side Scan Sonar; Sub-bottom Profiler (EdgeTech 2200M); Multi-Beam Echo Sounder (Kongsberg EM2000); CTD Sensor (Seabird)
Size (m):	4.5 x 6.0x 0.69
Speed (kts):	5
Battery Life (hrs):	~28-83(depending on the number of batteries)
Navigation Standard:	Inertial Navigation System; Doppler Velocity Log; Altimeter; GPS; Depth Sensor; USBL, LBL

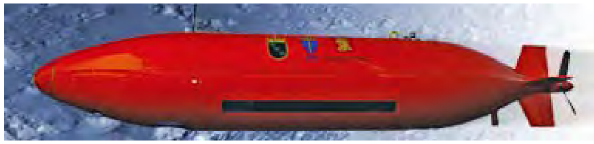
MISSION RECONFIGURABLE UUV (MRUUV)



http://archive.auvac.org

Status:	No longer in production
Year Launched:	Expected 2009
Manufacturer and Product Family:	Lockheed Martin, Mission Reconfigurable UUV (MRUUV)
Depth Rating (m):	n/a
Standard Sensors:	n/a
Size (m):	6.35 x 0.53
Speed (kts):	8
Battery Life (hrs):	40
Navigation Standard:	n/a

HUGIN 1000, 3000, 4500



http://www.km.kongsberg.com/

Status:	Currently manufactured
Year Launched:	2000
Manufacturer and Product Family:	Kongsberg Maritime, HUGIN 1000, 3000, 4500
Depth Rating (m):	1000, 3000, 4500
Standard Sensors:	Side Scan Sonar; Multi-Beam Echo Sounder; Sub-Bottom Profiler; CTD Sensor; Acoustic Doppler Current Profiler (1000: Synthetic Aperture Sonar; Forward Looking Sonar)
Size (m):	4.5 x 0.75; 5.5 x 1.0; 6.0 x 1.0
Speed (kts):	4-6
Battery Life (hrs):	17~30 (for 1000), 60
Navigation Standard:	Inertial Navigation Sensor; Doppler Velocity Log; Pressure; GPS; Ultra Short Baseline

BLUEFIN-21 BPAUV CONFIGURATION

http://archive.auvac.org

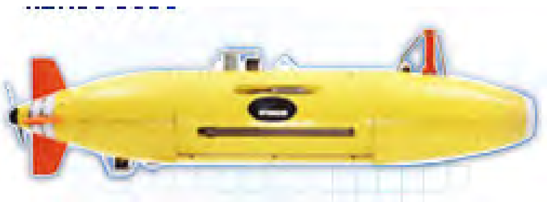
Status:	Currently manufactured
Year Launched:	2005 Manufacturer and Product Family: Bluefin Robotics Corp, Bluefin-21 BPAUV Configuration
Manufacturer and Product Family:	600
Depth Rating (m):	Side Scan Sonar
Standard Sensors:	1.83 x 0.53
Size (m):	4
Speed (kts):	18
Battery Life (hrs):	GPS; Intertial Measurement; Doppler Velocity Log; Compass; Pressure
Navigation Standard:	Currently manufactured

TALISMAN M

http://auvac.org

Status:	Currently manufactured
Year Launched:	2006
Manufacturer and Product Family:	BAE Systems, Talisman M
Depth Rating (m):	300
Standard Sensors:	Environmental Sensors; Forward Looking Sonar
Size (m):	4.5 x 2.5
Speed (kts):	~6
Battery Life (hrs):	~24
Navigation Standard:	n/a

REMUS 6000

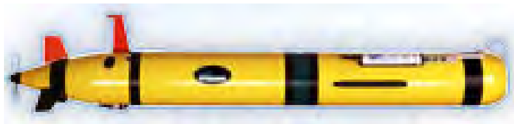


http://auvac.org

Status:	Currently manufactured
Year Launched:	2008
Manufacturer and Product Family:	Hydroid, REMUS 6000
Depth Rating (m):	6000
Standard Sensors:	Conductivity and Temperature; Acoustics Doppler Current Profiler; Side Scan Sonar; Pressure
Size (m):	3.084 x 0.71
Speed (kts):	4.5
Battery Life (hrs):	~22
Navigation Standard:	GPS; Intertial Navigation Unit; Long Baseline; 7-10Hz upward Looking; Dead reckoning with Doppler Velocity Log

A.2 Lightweight AUVs

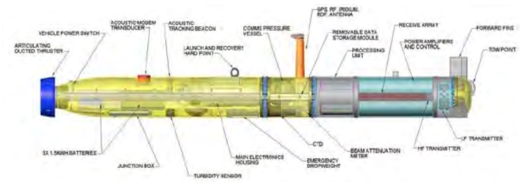
REMUS 600



http://www.esyntactic.com

Status:	Currently manufactured
Year Launched:	2003
Manufacturer and Product Family:	Hydroid, REMUS 600
Depth Rating (m):	600 m (1500 m, optional)
Standard Sensors:	Conductivity & Temperature; Acoustic Doppler Current Profiler; Side Scan Sonar; Pressure
Size (m):	3.25 x ø 0.324
Speed (kts):	~4.5
Battery Life (hrs):	70
Navigation Standard:	GPS; Inertial Navigation Sensor; Long Base Line, 7-10kHz upward looking; Dead Reckoning with Doppler Velocity Log

BLUEFIN-12 SMCM/UUV-2 CONFIGURATION



http://archive.auvac.org

Status:	Currently manufactured
Year Launched:	n/a
Manufacturer and Product Family:	Bluefin Robotics Corporation, Bluefin-12 SMCM/UUV-2 Configuration
Depth Rating (m):	200 m
Standard Sensors:	Configuration: Synthetic Aperture Sonar (QinetiQ Simultaneous Dual-Frequency SAS)
Size (m):	3.35 x ø 1.06
Speed (kts):	5
Battery Life (hrs):	n/a
Navigation Standard:	GPS; Inertial Measurement; Doppler Velocity Log; Compass; Pressure

TALISMAN L

http://www.defense.gouv.fr

Status:	Currently manufactured
Year Launched:	2009
Manufacturer and Product Family:	BAE Systems, Talisman L
Depth Rating (m):	100
Standard Sensors:	Environmental Sensors; Forward Looking Sonar
Size (m):	4.5 x 2.5 x1.1
Speed (kts):	7
Battery Life (hrs):	12
Navigation Standard:	n/a

SEAWOLF A

http://archive.auvac.org

Status:	Currently manufactured
Year Launched:	n/a
Manufacturer and Product Family:	Atlas Elektronik GmbH, Seawolf A
Depth Rating (m):	300
Standard Sensors:	Side Scan Sonar; Camera; CTD; Forward looking sonar
Size (m):	2 x 0.5 x 0.3
Speed (kts):	5
Battery Life (hrs):	3
Navigation Standard:	GPS

A.3 Portable AUVs

GAVIA AUV SYSTEM

http://auvac.org

Status:	Currently manufactured
Year Launched:	1999
Manufacturer and Product Family:	Hafmynd, the Gavia AUV system
Depth Rating (m):	200 , 500 , 1000 , 2000
Standard Sensors:	Side Scan Sonar; Forward Looking Sonar; Pressure; CTD Sensor; Bathymetry Sonar; Acoustic Doppler Current Profiler
Size (m):	>1.7 x ø 0.2
Speed (kts):	2-6
Battery Life (hrs):	Variable (multiple battery modules can be mounted)
Navigation Standard:	GPS; Magneto-inductive electronic compass and tilt-sensors; 3-axis rate gyros

REMUS 100

http://www.hydroidinc.com

Status:	Currently manufactured
Year Launched:	1995
Manufacturer and Product Family:	Hydroid, REMUS 100
Depth Rating (m):	100
Standard Sensors:	Side Scan Sonar; Acoustic Doppler Current Profiler; CTD
Size (m):	1.6 x ø 0.19
Speed (kts):	~4.5
Battery Life (hrs):	10hr@3 kts, <8 hr@5 kts
Navigation Standard:	Long Baseline; Ultra Short Baseline; Doppler Assisted Dead Reckoning

IVER2

http://auvac.org

Status:	Currently manufactured
Year Launched:	2003
Manufacturer and Product Family:	Oceanserver, Iver2
Depth Rating (m):	100 (200 , optional)
Standard Sensors:	n/a
Size (m):	1.27 x ø 0.147
Speed (kts):	1-4
Battery Life (hrs):	24 @ 2.5km
Navigation Standard:	Dead Reckoning

BLUEFIN-9 SEALION II CONFIGURATION

http://archive.auvac.org

Status:	Currently manufactured
Year Launched:	n/a
Manufacturer and Product Family:	Bluefin Robotics Corporation, Bluefin-9 SeaLion II Configuration
Depth Rating (m):	200
Standard Sensors:	Dual-Frequency Side Scan Sonar; CT; Low-light B/W Camera; Turbidity; Pressure
Size (m):	1.65 x ø 0.24
Speed (kts):	4
Battery Life (hrs):	12 @3 knots
Navigation Standard:	GPS; Inertial Measurement; Doppler Velocity Log; Compass; Pressure

SEAFOX IQ

http://archive.auvac.org

Status:	Currently manufactured
Year Launched:	n/a
Manufacturer and Product Family:	Atlas Elektronik GmbH, SeaFox IQ
Depth Rating (m):	300
Standard Sensors:	n/a
Size (m):	1.3 x ø 0.4
Speed (kts):	6
Battery Life (hrs):	2
Navigation Standard:	GPS; Doppler Velocity Log; Inertial Measurement

Annex B Examples of Remotely Operated Vehicles

COUGAR XT

http://www.seaeye.com

Year Launched:	2002
Manufacturer and Product Family:	Saab, Cougar XT
Camera Tilt/Pan:	180˚, Optional 340˚
Depth Rating (m):	2000
Sensors:	Standard
Size (mm):	1506 x 745 x 1000
Speed (kts):	3.2
Weight (kg)	344
Tools	2 x 5F

SURVEYOR PLUS

http://www.seaeye.com

Year Launched:	2002
Manufacturer and Product Family:	Saab, Surveyor Plus
Camera Tilt/Pan:	180˚, optional 340˚
Depth Rating (m):	600
Sensors:	Optional
Size (mm):	1450 x 920 x 820
Speed (kts):	3
Weight (kg)	250
Tools	1 x 5F

PANTHER PLUS

http://www.seaeye.com

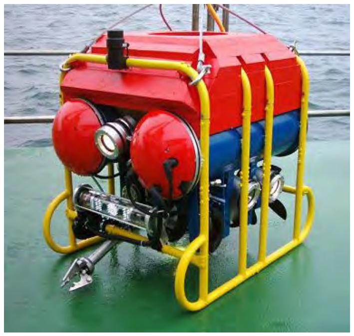
Year Launched:	2002
Manufacturer and Product Family:	Saab, Panther Plus
Camera Tilt/Pan:	340˚
Depth Rating (m):	1000
Sensors:	Optional
Size (mm):	1750 x 1217 x 1060
Speed (kts):	3
Weight (kg)	500
Tools	1 x 5F and 1 x 6F

JAGUAR

http://www.seaeye.com

Year Launched:	2002
Manufacturer and Product Family:	Saab, Jaguar
Camera Tilt/Pan:	340˚
Depth Rating (m):	3000
Sensors:	Optional
Size (mm):	2200 x 1500 x 1325
Speed (kts):	>3
Weight (kg)	1300
Tools	Job specific skid

DiveAgent



http://www.hydrosupport.com

Year Launched:	2005
Manufacturer and Product Family:	HydroSupport, DiveAgent
Camera Tilt/Pan:	320˚
Depth Rating (m):	400
Sensors:	Standard
Size (mm):	700 x 650 x 600
Speed (kts):	2
Weight (kg)	100
Tools	1 x 3F

Sirio

http://www.nautec.it

Year Launched:	2001
Manufacturer and Product Family:	NAUTEC SRL, Sirio
Camera Tilt/Pan:	180˚
Dept□ Rating (m):	300
Sensors:	n/a
Size (mm):	590 x450 x560
Speed (kts):	1.5
Weight (kg)	40
Tools	1 x 2F

PERSEO

http://www.nautec.it

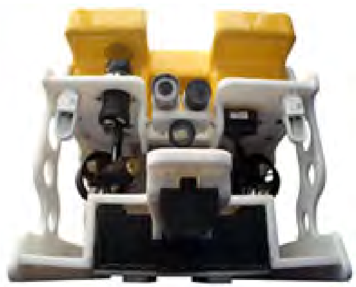
Year Launched:	2001
Manufacturer and Product Family:	NAUTEC SRL, DiveAgent
Camera Tilt/Pan:	180˚
Dept□ Rating (m):	600
Sensors:	Standard
Size (mm):	980 x 510 x 710
Speed (kts):	2
Weight (kg)	80
Tools	Optional: multifunctional mini-manipulator

PERSEO GT

http://www.nautec.it

Year Launched:	2□01
Manuf□cturer and Product Family:	NAUTEC SRL, Perseo GT
Camera Tilt/Pan:	n/a
Depth Rating (m):	600 or 1500 with TMS
Sensors:	Standard
Size (mm):	980 x 510 x 800
Speed (kts):	3.5
Weight (kg)	90
Tools	Optional: multifunctional mini-manipulator

PEGASO



http://www.nautec.it

Year Launched:	2001
Manufacturer and Product Family:	NAUTEC SRL, Pegaso
Camera Tilt/Pan:	Tilt and Pan
Depth Rating (m):	600 or 1500 with TMS
Sensors:	Standard
Size (mm):	1500 x 800 x1000
Speed (kts):	3.2
Weight (kg)	350
Tools	2/4 or 5/6 functions mounted on skids

OUTLAND 1000

http://www.seatrepid.com

Year Launched:	1999
Manufacturer and Product Family:	Outland Technology Inc., Outland 1000
Camera Tilt/Pan:	360˚
Depth Rating (m):	300
Sensors:	Optional
Size (mm):	650 x 260 x 370
Speed (kts):	3
Weight (kg)	17.7
Tools	Optional

UHD Ultra Heavy Work-Class ROV

http://schilling.com/products

Year Launched:	2004
Manufacturer and Product Family:	Schilling Robotics, UHD Ultra Heavy Work-Class ROV
Camera Tilt/Pan:	300˚
Depth Rating (m):	4000
Sensors:	Standard
Size (mm):	3000 x 2100 x 1900
Speed (kts):	2
Weight (kg)	5000
Tools	Options: 5 function, 7 function, customer-specified

LBV150S

http://www.seabotix.com

Year Launched:	2001
Manufacturer and Pr□duct Family:	SeaBotix Inc.; LBV150S
Camera Tilt/Pan:	180˚
Depth Rating (m):	150
Sensors:	Optional
Size (mm):	530 x 254 x 245
Speed (kts):	3
Weight (kg)	12
Tools	Optional

LBV200L	LBV300S-6
 http://seaviewsystems.com	 http://www.seabotix.com

LBV200L

Year Launched:	2001
Manufacturer and Product Family:	SeaBotix Inc.; LBV200L
Camera Tilt/Pan:	180˚
Depth Rating (m):	200
Sensors:	Optional
Size (mm):	530 x 254 x 245
Speed (kts):	3
Weight (kg)	12
Tools	Optional

LBV300S-6

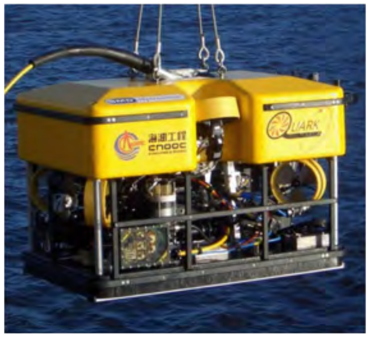
Year Launched:	2005
Manufacturer and Product Family:	SeaBotix Inc.; LBV300S-6
Camera Tilt/Pan:	180˚
Depth Rating (m):	300
Sensors:	Optional
Size (mm):	530 x 254 x 484
Speed (kts):	4
Weight (kg)	15.3
Tools	Optional

LBV600XL

http://www.rovexchange.com

Year Launched:	2005
Manufacturer and Product Family:	SeaBotix Inc.; LBV600XL
Camera Tilt/Pan:	180˚
Depth Rating (m):	600
Sensors:	Optional
Size (mm):	530 x 270 x484
Speed (kts):	4
Weight (kg)	15.3
Tools	Optional

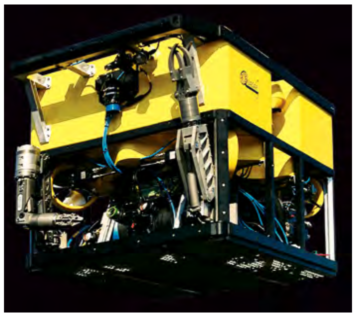
QUARK



http://www.act-us.info

Year Launched:	2004
Manufacturer and Product Family:	SMD Hydrovision ; QUARK
Camera Tilt/Pan:	Pan and Tilt
Depth Rating (m):	1000, Optional: 500, 2000, 3000
Sensors:	Standard
Size (mm):	2000 x 1300 x 1400
Speed (kts):	3.2
Weight (kg)	1500
Tools	Options: 5 function, 7 function, customer-specified

QUASAR COMPACT



http://smd.co.uk

Year Launched:	2004
Manufacturer and Product Family:	SMD Hydrovision; QUASAR Compact
Camera Tilt/Pan:	Pan and Tilt
Depth Rating (m):	3000 ,Optional:500, 1000, 2000, 4000
Sensors:	n/a
Size (mm):	2300 x 1500 x 1500
Speed (kts):	3.2
Weight (kg)	2300
Tools	Options:5 function 7 function, customer-specified

QUASAR

http://www.act-us.info

Year Launched:	2004
Manufacturer and Product Family:	SMD Hydrovision; QUASAR
Camera Tilt/Pan:	Pan and Tilt
Depth Rating (m):	3000, Optional:500, 1000 , 2000, 4000
Sensors:	Standard
Size (mm):	3100 x 1800 x 1800
Speed (kts):	3.2
Weight (kg)	3500
Tools	Options:5 function, 7 function, customer-specified

QUANTUM

http://www.rovexchange.com

Year Launched:	2004
Manufacturer and Product Family:	SMD Hydrovision; QUANTUM
Camera Tilt/Pan:	Pan and Tilt
Depth Rating (m):	3000, optional: 500, 1000, 2000, 4000
Sensors:	Standard
Size (mm):	2300 x 1500 x 1500
Speed (kts):	3.2, optional: 3.5
Weight (kg)	4750
Tools	Options: 5 function, 7 function, customer-specified

List of symbols/abbreviations/acronyms/initialisms

°C	Degrees Celsius
ASW	Anti-Submarine Warfare
ATR	Automated Target Recognition
AUV	Autonomous Underwater Vehicle
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance
CF	Canadian Forces
CT	Contact Temperature
CURV	Cable-Controlled Underwater Research Vehicle
DSIS	Deep Sea Intervention System
DND	Department of National Defence
DRDC	Defence Research & Development Canada
DVL	Doppler Velocity Log
GPS	Global Positioning System
HDTV	High definition television
hp	Horsepower
Hz	Hertz
INS	Inertial Navigation System
ISR	Intelligence, Surveillance and Reconnaissance
kHz	Kilohertz
km	Kilometres
LBL	Long Baseline
LOA	Level of Automation
m	Metres
MCM	Mine Countermeasures
MHz	Megahertz
PC	Personal Computer
ROV	Remotely Operated Vehicle
SA	Situation Awareness
SBL	Short Baseline
SPM	Self-Protective Measures

UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
UUV	Unmanned Underwater Vehicle
US	United States
USDOD	United States Department of Defense
USBL	Ultra Short Baseline

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Human Factors Issues When Operating Underwater Remotely Operated Vehicles and Autonomous Underwater Vehicles (U)
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(U) There has been a great deal of human factors research on unmanned air vehicles (UAVs) and unmanned ground vehicles (UGVs) in large due to a high number of operator related mishaps. However, there is very little research examining the unique human factors problems associated with unmanned underwater vehicles (UUVs). The lack of research is surprising as there are frequent anecdotal accounts ROV entanglement, collisions, and failures. In addition, militaries are now using UUVs for search and rescue and mine countermeasure (MCM) operations and in the future, UUVs will take on critical roles in intelligence, surveillance, and reconnaissance (ISR), anti−submarine warfare (ASW) and even time critical strike operations. In this paper, it is argued that the underwater environment presents unique challenges to operating UUVs that are different from the challenges of UGV and UAV systems. Several common human factors problems are discussed when using UUVs, including the loss of sensory cues and spatial awareness, the control of the remote vehicle, problems with situation awareness and workload, problems with trust in automation, and challenges with human robot communication. In each case, these issues are discussed with respect to underwater operations.

(U) En bonne partie en raison du nombre élevé de contretemps liés aux opérateurs, on a fait beaucoup de recherches sur les facteurs humains liés aux engins télépilotés aériens (UAV) et aux engins télépilotés terrestres (UGV). Il existe cependant très peu de recherches sur les problèmes particuliers aux facteurs humains associés aux engins télépilotés sous marins (UUV). Ce faible nombre de recherches est surprenant, car il y a souvent des comptes rendus anecdotiques d’enchevêtrements, de collisions et de pannes de ROV. De plus, des militaires utilisent maintenant les UUV pour des opérations de recherche et sauvetage ainsi que de lutte contre les mines (LCM) et, dans le futur, les UUV joueront des rôles essentiels dans le renseignement, la surveillance et la reconnaissance (RSR), la lutte anti sous marine (LASM) et même dans les opérations offensives à durée critique. Dans le présent document, on allègue que le milieu sous marin présente des défis particuliers à l’exploitation d’UUV qui diffèrent de ceux que présentent les systèmes UGV et UAV. Plusieurs problèmes courants liés aux facteurs humains sont traités lors de l’utilisation d’UUV, notamment la perte de repères sensoriels et d’orientation spatiale, la commande de l’engin télépiloté, les problèmes de conscience de la situation et de la charge de travail, les problèmes de confiance en l’automatisation ainsi que les défis que constitue la communication entre les humains et les robots. Dans chaque cas, on traite de ces questions en rapport avec les opérations sous marines.

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(U) human factors issues; UUV; ROV; AUV

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